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# Combustion Analysis in an Optical Access Engine

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**Abstract**

The ever more strict pollutant emissions regulations urge to make further steps in the evolution of the internal combustion engines, in particular as far as the emissions generation. A direct observation of the phaenomena taking place inside the cylinder can hence help in better understanding the effects obtainable by using different solutions (injection systems, ignition systems,… ).
To this end, the use of an optical access engine can be very helpful. This paper presents the first step made at the Department of Industrial Engineering of the University of Perugia for the set-up of an experimental line to be used for the analysis of combustion events observed in a single cylinder optical access engine.
The combustion was characterized by using different techniques: thermodynamic (heat release) based on in-cylinder pressure measurements, and non intrusive optical observations by means of images acquisition. The flame images collected by a synchronized CCD camera were post-processed in order to evaluate the rates of the in-cylinder flame front evolution, observing the combustion process from the flame kernel formation on.
Different fuels were used in the spark ignition, four valves, optical access engine: pure gasoline, pure ethanol, a 50% gasoline/ethanol blend. The experimental tests were carried out at 900 rpm engine speed, in rich and lean conditions, the latter being of interest for the achievement of significant CO2 reduction.



*Keywords:* alternative fuels; combustion; CO2 reduction

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## 1. Introduction

Despite the current effort devoted by the automotive industry to the development of vehicles equipped with innovative propulsion systems (e.g. hybrid, electric,…), it is commonly believed that the use of internal combustion engines will still remain dominant for decades. At the same time, the attention of governments to impose ever more stringent limits for pollutant emissions is constant, and special consideration is given to the reduction of CO2.

**Nomenclature**

| | |
|---|---|
| $R_{ff}$ | deflagration front radius |
| $V_{ff}$ | deflagration front speed |
| Xb | mass fraction burned |
| $\Phi$ | equivalence ratio |

*Abbreviations*

| | |
|---|---|
| AIT | After Ignition Timing |
| BTDC | Before intake Top Dead Centre |
| ATDC | After intake Top Dead Centre |
| CA | Crank Angle |
| GDI | Gasoline Direct Injection |
| EVC | Exhaust Valve Closure |
| EVO | Exhaust Valve Open |
| IVC | Intake Valve Closure |
| IVO | Intake Valve Opening |
| LIF | Laser Induced Fluorescence |
| MBT | Minimum spark advance for Best Torque |
| PFI | Port Fuel Injection |
| PIV | Particle Image Velocimetry |
| rpm | Revolutions Per Minute |
| SI | Spark Ignition |
| SA | Spark Advance Timing |

To answer these problems, the internal combustion engines are facing a new step in their evolution, which is essential for the support of an even deeper scientific analysis. In fact, only a further understanding can enable the realization of engines that produce lower quantities of gas pollutants in the combustion chamber. In spite of many scientific studies carried out in more than 150 years and the development, in the last 30, of simulation tools ever more sophisticated, it seems necessary to further study of phenomena such as combustion in ultra lean conditions, or the use of bio-fuels, pure or in blends with fossil ones.

This paper presents the first step made at the Department of Industrial Engineering of the University of Perugia for the set-up of an experimental line to be used for the analysis of combustion events observed in a single cylinder optical access engine. These type of test bench is very flexible and can allow the use of several different techniques, based on different measurements approaches, either conventional as the thermodynamic ones (heat release analysis based on in-cylinder pressure measurements) or non-intrusive optical ones, as high-speed camera imaging [1], spectroscopy [2, 3], PIV [4], LIF [5], etc.

The characterization of the combustion remains a challenge of main interest, in particular if alternative fuels, to be used pure or in blends with fossil fuels, are considered. A deeper insight in the evolution of the combustion processes of such fuels, in engines adopting more or less conventional configurations ( PFI, DDI,… vs. GDI, HCCI, …), or new ignition systems (plasma, multiple spark,…), could help to make possible further steps in the development of systems characterized by ever lower emissions and fuel consumption levels.

Direct observations are also very useful for the set-up and check of suitable sub-models to be used in CFD-3D simulation codes, in order to allow an ever more efficient optimization, while also engine control algorythms can take advantage from a direct check in an optical access engine.

The present work describes the current development level of the optical access engine test bench installed at the Department of Industrial Engineering. The experimental line was equipped with an in-cylinder pressure measurement gauge for the heat release analysis, while a synchronized CCD camera was used in order to characterize the deflagration front evolution, by post-processing and analysing the acquired images for the flame growth rate evaluation.

The tests reported in this paper were carried out by using different fuels: pure gasoline, pure ethanol, a 50% gasoline/ethanol blend; the main engine operational parameters were: 900 rpm engine speed, rich ( $\phi$=1.1 ) and lean ( $\phi$ = 0.9 ) air-fuel mixture conditions.

## 2. Experimental set-up and test procedures

The optical access engine that was set up and used in this work is shown in Fig. 1. The combustion chamber can be observed through a conventional prolonged piston, which allows the housing of a 60 mm diameter flat quartz window and of a 45° mirror. The engine is connected to an AVL 5700 dynamic brake, while a heating/cooling unit allows the control of the engine oil and coolant fluid temperatures.

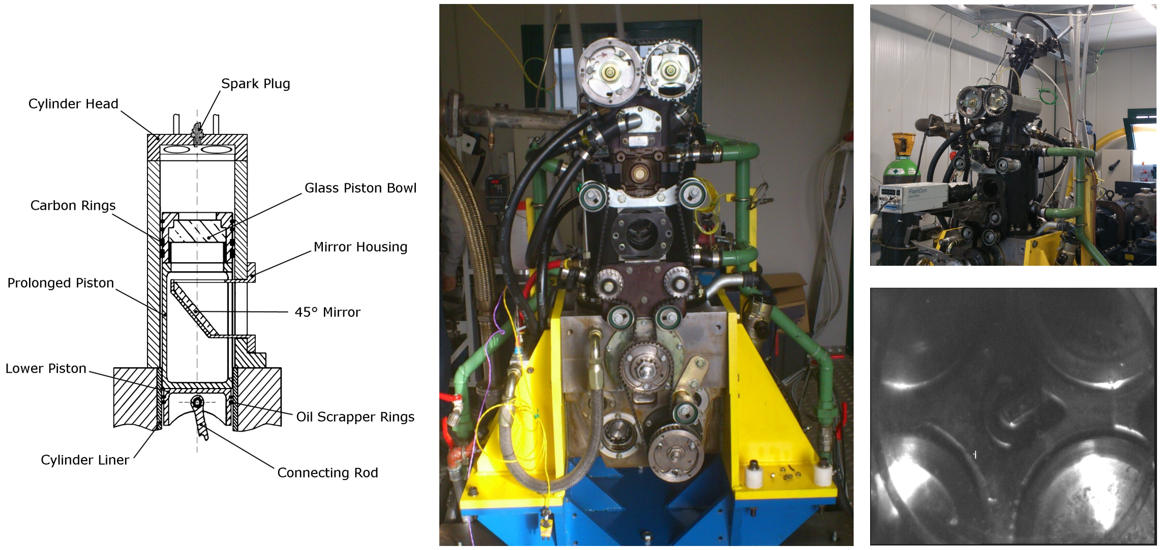


Fig. 1. The single-cylinder optical access engine.

In order to avoid the quick fouling of the quartz window, lubrication oil can not be used; consequently, for a safe cylinder/piston coupling operation the prolonged piston mounts two graphite rings. In order to decrease the pressure losses from the combustion chamber, one of these rings was modified by designing and applying an intermediate "C" shaped cast iron ring which contains the graphite ring.

The research engine allows different configurations, i.e. either spark or compression ignition. The current set-up is spark ignition, equipped with two types of injectors, GDI and PFI; in this work the PFI was actually used.

In addition to the main optical access through the prolonged piston, two other, smaller, accesses are placed by opposite sides of the 4 valves prototype head. The main engine characteristics are reported in Table 1. One of these lateral accesses was used to place a piezoelectric pressure transducer, Kistler 6061B, connected to a Kistler 5011 charge amplifier. The pressure acquisitions are performed by sampling data as a function of 0.2 degree CA resolution signal, provided by an AVL 364 optical encoder.

Table 1. Optical access research engine specifications.

| | | |
|---|---|---|
| Cylinders | 1 | |
| Cycle | 4-Stroke | |
| Valves | 2 Intake, 2 Exhaust | |
| Bore | 85.0 mm | |
| Stroke | 88.0 mm | |
| Compression ratio | 8.8 : 1 | |
| Valve timings | IVO 34° CA BTDC, | IVC 199° CA ATDC, |
| | EVO 526° CA ATDC, | EVC 25° CA ATDC |

All the acquisition and control functions are performed by suitable LabView programs developed by the authors, that drive National Instruments data acquisition systems. A National Instruments PCI IMAQ-1408 frame grabber collects the video signal sent by a PCO Flashcam 335-CG CCD camera, that provides 636x576 pixel resolution images. This camera, although characterized by a standard frame rate, can be synchronized with external events and records images with variable acquisition lengths and delay times from the trigger.

A suitable post-processing procedure was set-up, in order to determine the characteristics of the flame developement, by evaluating the growth in time of the deflagration front position. To this end the images are treated applying a thresholding/binarization process, followed by the calculation of the area relevant to the flame progress and of the corresponding radius of a circle of equivalent area (Fig.2).

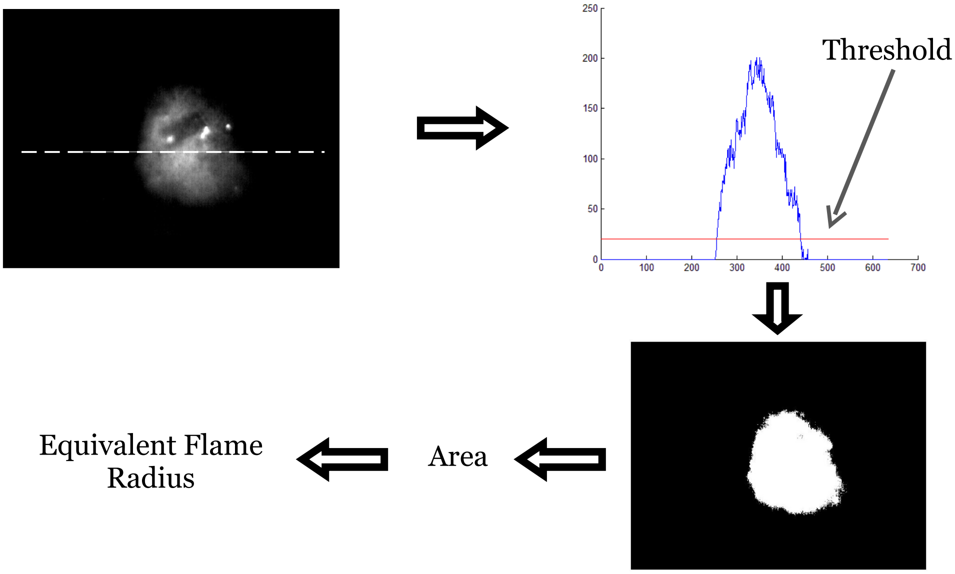


Fig. 2. Post-processing procedure.

Since the currently used CCD camera does not allows high speed image recordings, necessary for CA-resolved acquisitions, were perfomed acquisitions of images series each pertaining at a different delay from the ignition time, ranging from 400 µs to 2000 µs, corresponding to the 2° - 11° CA after the ignition range. An example of the collected images is reported in Fig. 3.

For each single image it was applied the post-processing procedure, measuring the flame equivalent radius and the corresponding flame growth speed.

The programmable ECU used to control injection and ignition was connected to a conventional Lambda sond put in exhaust duct; in order to check the actual obtained mixture condition was however installed a fast response Lambda-NOx sensor Horiba MEXA-720.


Fig. 3. Flame development at 4.4°, 5.4°, 6.5°, 7.6°, 8.7°, 9.8°, 10.8° CA AIT.

## 1. Results

The in-cylinder pressure data were collected in tests performed at 900 rpm, in rich ( $\phi$=1.1 ) and lean ( $\phi$ = 0.9 ) conditions, with the three different fuel compositions, G100, E100 and B50. The same SA=17° CA was used in all runs, corresponding to the MBT relevant to the gasoline operation. This SA value was used for all fuels, so that the ignition could take place in possibly similar in cylinder flow conditions.

The traces corresponding to the pressure averaged values are reported in Fig.4. As expected, the highest value of the in cylinder maximum pressure is achieved by using ethanol, for both mixture conditions, while the lowest pertains to gasoline. The time at which the pressure peak is reached is in advance for the ethanol if compared to the other fuels: the ethanol faster combustion is confirmed by the analysis of the MFB graphic, reported in Fig.5. As far as the 50% blend is concerned, it behaves, as expected, with intermediate characteristics if compared to pure fuels; however, at early stages of the combustion, tend to show trends closer to the ethanol ones. The previous remarks apply similarly for both of the examined mixture conditions.

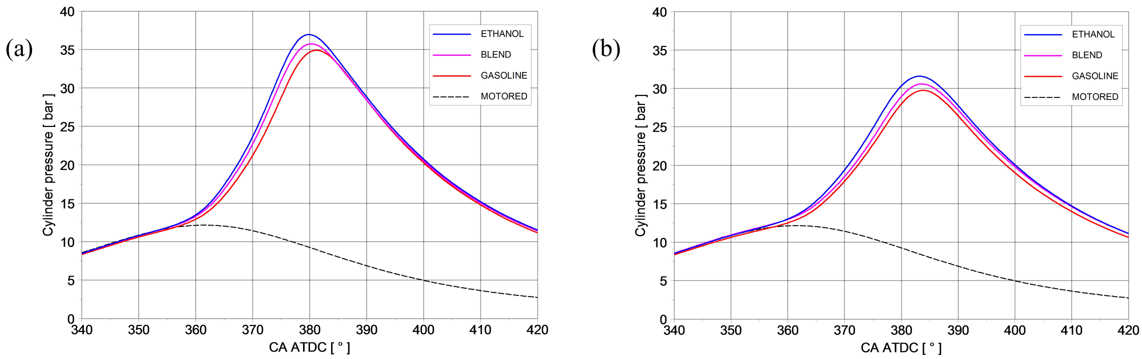


Fig. 4. In-cylinder pressure: (a) $\phi$=1.1; (b) $\phi$=0.9.

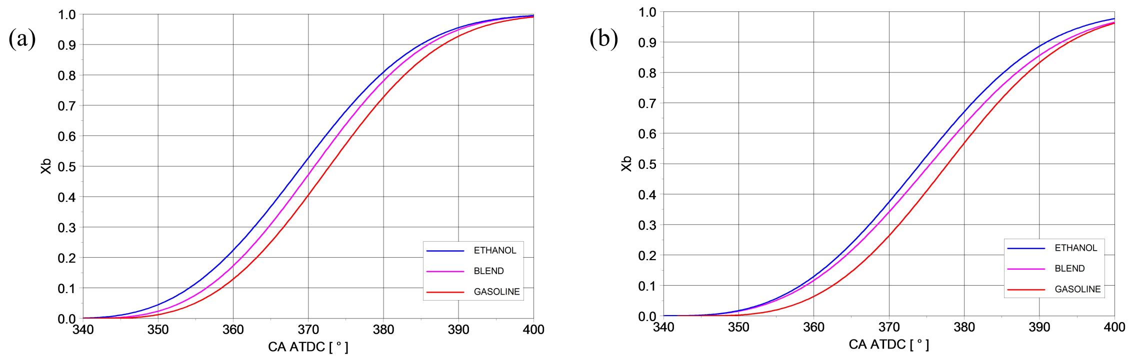


Fig. 5. Mass fraction burned: (a) $\phi$=1.1; (b) $\phi$=0.9.

Flame observations were performed at 900 rpm, in rich ( $\phi$=1.1 ) mixture conditions, with two fuel compositions: G100 and E100. After the post-processing procedure of the collected images, the flame front growth radius was calculated, as reported in Fig.6 as a function of the CA after the ignition.

It can be noted that the image analysis confirms the results of the thermodynamic one (MFB), clealry confirming the faster combustion characteristics of the ethanol fuel. Also in terms of flame growth speed the faster behaviour of the ethanol is confirmed by the trends shown in Fig.7, obtained by deriving the interpolating curves plotted in Fig.6. The ethanol behaviour is also confirmed by the observation of the flame pictures reported in Fig.3: the differences between the flames of the two fuels are evident, in particular the luminosity, lower for gasoline at all stages.

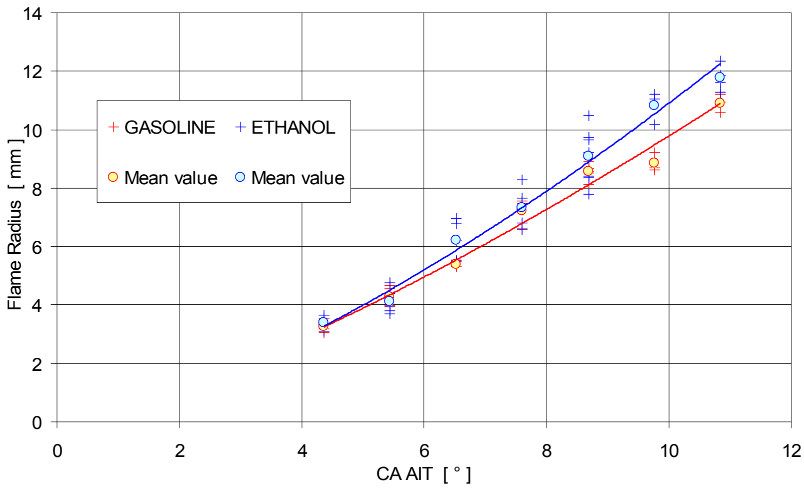


Fig. 6. Flame radius.

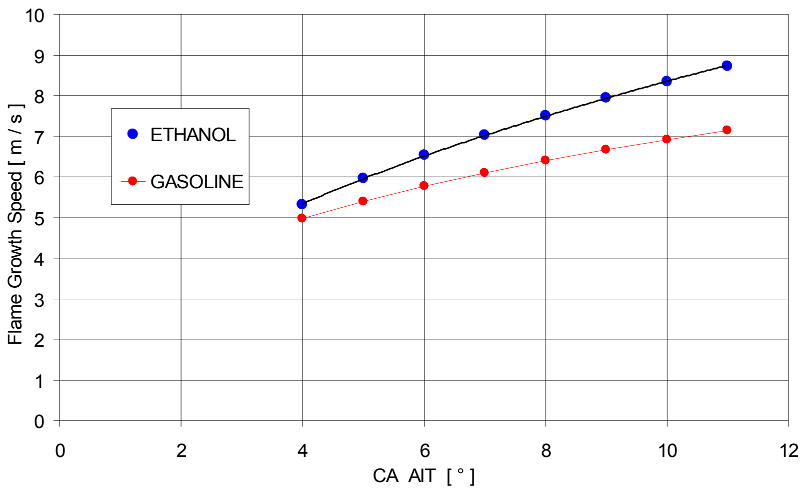


Fig. 7. Flame growth speed.

## 4. Conclusions and future work

In this paper the set-up of a test bench based on an optical access engine was presented. First analyses were carried out by using different blend: gasoline, ethanol and a 50% blend of them.

A thermodynamic analysis was performed, determining the combustion characteristics in terms of in-cylinder pressure and mass fraction burned, showing a faster combustion behaviour of the ethanol, if compared to the blend and to the gasoline. These trends were similar in different mixture conditions.

Despite the use of a standard speed CCD camera, the adopted methodology has however allowed a suitable the evaluation of the deflagration front evolution in terms of flame growth radius and of flame growth speed. The results of the test performed with gasoline and ethanol confirmed the fast combustion characteristics of the latter, also corresponding to a higher flame luminosity.

The experimental bench that was set up and tested in this work, will be used to test a wider range of operating conditions: the results will also be used by the same research group to develop and check sub-models of numerical codes.

At the same time, a further evolution in the set-up will be achieved, by acquiring a high-speed camera, in order to collect angle resolved images.

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